



Electronics for Deep Space Cryogenic Applications

R.L. Patterson
Glenn Research Center, Cleveland, Ohio

A. Hammoud
QSS Group, Inc., Cleveland, Ohio

J.E. Dickman
Glenn Research Center, Cleveland, Ohio

S.S. Gerber
ZIN Technologies, Inc., Brook Park, Ohio

M.E. Elbuluk
University of Akron, Akron, Ohio

E. Overton
Glenn Research Center, Cleveland, Ohio

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R.L. Patterson
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

A. Hammoud
QSS Group, Inc.
Cleveland, Ohio 44135

J.E. Dickman
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

S. Gerber
ZIN Technologies, Inc.
Brook Park, Ohio 44142

M.E. Elbuluk
University of Akron
Akron, Ohio 44325

E. Overton
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract: Deep space probes and planetary exploration missions require electrical power management and control systems that are capable of efficient and reliable operation in very cold temperature environments. Typically, in deep space probes, heating elements are used to keep the spacecraft electronics near room temperature. The utilization of power electronics designed for and operated at low temperature will contribute to increasing efficiency and improving reliability of space power systems. At NASA Glenn Research Center, commercial-off-the-shelf devices as well as developed components are being investigated for potential use at low temperatures. These devices include semiconductor switching devices, magnetics, and capacitors. Integrated circuits such as digital-to-analog and analog-to-digital converters, DC/DC converters, operational amplifiers, and oscillators are also being evaluated. In this paper, results will be presented for selected analog-to-digital converters, oscillators, DC/DC converters, and pulse width modulation (PWM) controllers.

1. INTRODUCTION

Planetary exploration missions and deep space probes require electrical power management and control systems that are capable of efficient and reliable operation in very low temperature environments. Presently, spacecraft operating in the cold environment of deep space carry a large number of radioisotope heating units in order to maintain the surrounding temperature of the on-board electronics at approximately 20 °C.

In addition to deep space applications, low temperature electronics have potential uses in terrestrial applications that include magnetic levitation transportation systems, medical diagnostics, cryogenic instrumentation, and super-conducting magnetic energy storage systems. The utilization of power electronics designed for and operated at low temperature is expected to result in more efficient systems than room temperature systems. This improvement results from better electronic, electrical, and thermal properties of materials at low temperatures [1–3]. In particular, the performance of certain semiconductor devices improves with decreasing temperature down to liquid nitrogen temperature ($-196\text{ }^{\circ}\text{C}$) [3,4]. At low temperatures, majority carrier devices demonstrate reduced leakage current and reduced latch-up susceptibility. In addition, these devices show higher speed resulting from increased carrier mobility and saturation velocity [3–5]. An example is the power MOSFET that has lower conduction losses at low temperature due to the reduction in the drain-to-source resistance $R_{DS(on)}$ resulting from increased carrier mobility [4,6,7].

2. NASA GLENN RESEARCH CENTER LOW TEMPERATURE ELECTRONICS PROGRAM

The Low Temperature Electronics Program at the NASA Glenn Research Center (GRC) focuses on research and development of electrical components and systems suitable for applications in deep space missions. Research is being conducted on devices and systems for use down to cryogenic temperature ($-196\text{ }^{\circ}\text{C}$). The goal of the low temperature electronics program is to develop and demonstrate reliable, efficient, power systems capable of surviving and exploiting the advantages of low temperature environments. The targeted systems are mission-driven and include converters, inverters, controls, digital circuits, and special-purpose circuits. Initial development efforts have produced the successful demonstration of low temperature operation and cold-restart of several DC/DC converters (with outputs from 5 to 1000 Watts) utilizing different design topologies [1,4,7]. Some of these circuits employed superconducting inductors.

In support of system development, device and component research and development efforts are underway in critical areas of passive and active components, optoelectronic devices, and energy generation and storage. Initially, commercial-off-the-shelf (COTS) devices and components are characterized in terms of their performance at low-temperatures. When viable commercial devices fail to meet mission requirements, efforts are then undertaken to develop advanced components.

3. LOW TEMPERATURE R&D ACTIVITIES

3.1 Analog-to-Digital Converters

A commercial off-the-shelf 12-bit serial CMOS analog-to-digital converter, which was rated for operation between $-40\text{ }^{\circ}\text{C}$ and $+85\text{ }^{\circ}\text{C}$, was evaluated from room temperature to $-190\text{ }^{\circ}\text{C}$ in a liquid nitrogen cooled chamber. Parameters investigated included voltage conversion and control signal timing at a switching frequency of 100 kHz. Although the device had a built-in internal voltage reference, tests were also carried out using an external voltage reference. In either case, the device was able to provide the voltage conversions throughout the entire test temperature range down to $-190\text{ }^{\circ}\text{C}$. The converted output obtained using an external voltage reference, however, was more accurate than those obtained with an internal voltage reference. Results obtained at three different temperatures with an external reference are shown in Table 1.

3.2 Oscillators

A number of oscillators were designed and evaluated for low temperature operation. Figure 1 shows normalized frequency for an uncompensated silicon FET oscillator, an uncompensated oscillator designed for ultra low temperature, and a compensated oscillator modified for low temperature operation. It can be seen clearly that only the compensated modified oscillator was able to hold frequency, namely within ± 0.3 parts per million from $+85^{\circ}\text{C}$ down to -189°C .

3.3 DC/DC Converters

Several DC/DC converters have been built and characterized, in-house, at low temperatures. The converters were designed or modified to operate from room temperature to -196°C using commercially available components such as CMOS-type devices and MOSFET switches. These systems had output power range from 5 W to 1 kW with switching frequencies of 50 kHz to 200 kHz. Pulse width modulation technique was implemented in most of these systems with open-loop as well as closed-loop control. The topologies included buck, boost, multi-resonant, push-pull and full-bridge configuration [8–11].

In addition, several commercially available DC/DC converter modules were investigated for potential use at low temperatures. For example, the output voltage of a commercial DC/DC converter at various load levels is shown as a function of temperature in Figure 2. It can be seen that the output voltage of this particular module tends to be steady only between $+20^{\circ}\text{C}$ and -20°C . A slight reduction occurs in voltage regulation as temperature is further decreased to -80°C . Beyond that temperature, the converter tends to become unstable in terms of voltage regulation. This behavior occurs regardless of the levels of the applied input voltage and connected output load.

Another commercial DC/DC module included in this investigation fared relatively well in terms of its output regulation with temperature. The output voltage of this converter is depicted in Figure 3 as a function of temperature at various load levels.

3.4 PWM Controllers

Current-mode and voltage-mode pulse width modulation controllers were evaluated extensively for low temperature operation. The performance of one of those commercial grade pulse width modulation controller chips was evaluated between 25°C and -190°C . The device displayed acceptable performance throughout the entire test temperature range. Waveforms of the device reference voltage, oscillator, and output switching voltage, which were recorded at a control voltage (VC) of 1.5V, are shown in Figures 4 and 5 at test temperature of 25°C and -190°C , respectively. It can be seen clearly that all investigated properties did not undergo much change with temperature, as evident from the similarity of the waveforms shown for both extreme temperature, i.e., 25°C and -190°C .

4. CONCLUSION

The research efforts are focused on developing selected, mission-driven, power systems and supporting technologies for low temperature operation. The on-going low temperature activities include dielectric research and evaluation, power component development, and electronic system integration and demonstration. Other research investigations comprise long-term reliability assessment of power devices and integrated circuits and the effects of low temperature exposure on device interconnect and packaging.

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Table 1. Converted output voltage at various temperatures.

Input (V)	Output @ 25 °C	Output @ -100 °C	Output @ -190 °C
0	0.007	0.010	0.010
0.5	0.505	0.498	0.508
1	1.004	1.006	1.004
2	2.000	2.002	1.993
5	4.994	4.994	5.001
7.25	7.241	7.228	7.226
10	9.983	9.963	9.963
10.1	10.000	10.000	10.000

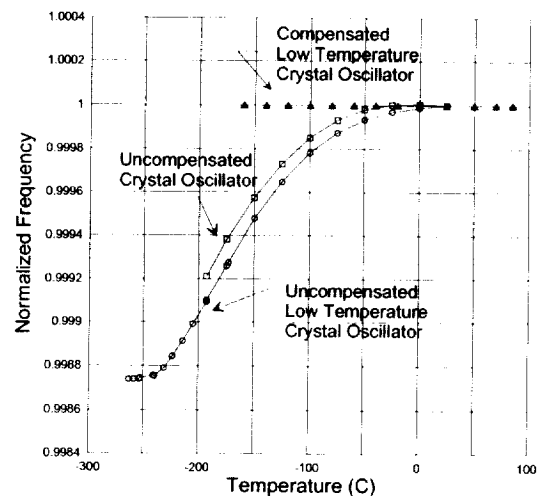


Figure 1. Normalized frequency output for three types of oscillators.

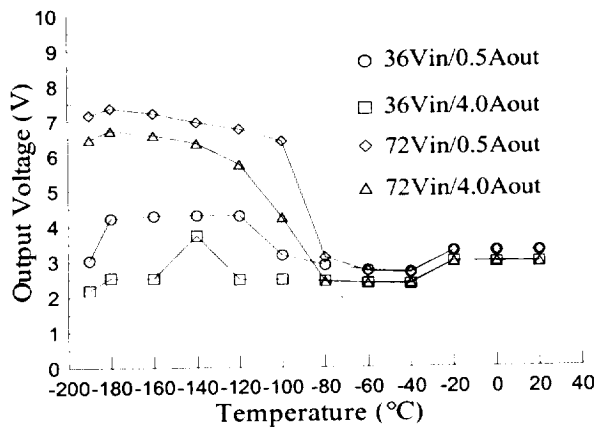


Figure 2. Poor performance of one commercial dc/dc converter module.

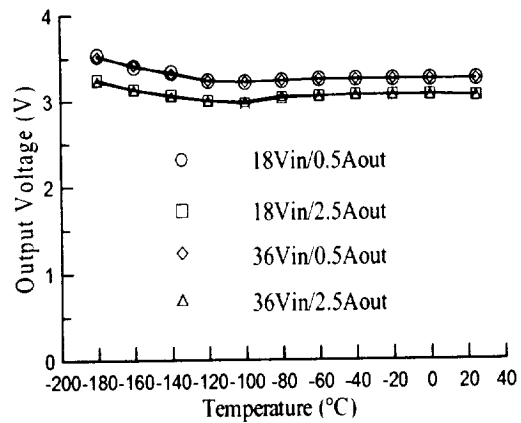


Figure 3. Superior performance of another commercial dc/dc converter.

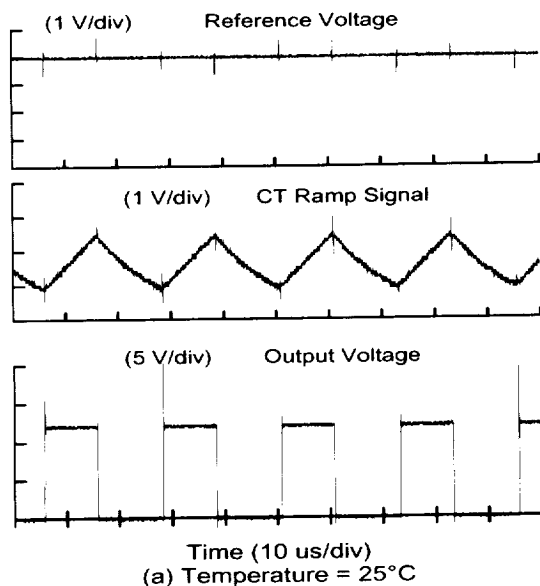


Figure 4. Waveforms of PWM Controller at 25 °C.

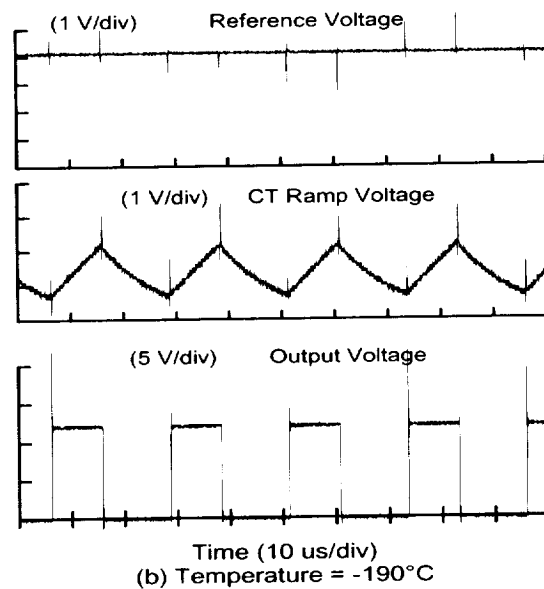


Figure 5. Waveforms of PWM Controller at -190 °C.

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